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Technical Report
February 1977

ANTENNA PATTERN SYNTHESIS COMPUTER PROGRAM

Syracuse University

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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Optimization techniques have been applied to the antenna pattern synthesis problem using point sources and ignoring the mutual coupling effects. If these effects are to be taken into account, it becomes very costly to perform the synthesis. In this report an approximate way to solve this problem has been prepared and implemented on a computer program.

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PREFACE

This effort was conducted by Syracuse University under the sponsorship of the Rome Air Development Center Post-Doctoral Program for Air Force Communications Service. Robert Bigelow of AFCS was the task project engineer and provided overall technical direction and guidance. The authors of this report are Dr. Jose Perini and Kazuhiro Hirasawa.

The RADC Post-Doctoral Program is a cooperative venture between RADC and some sixty-five universities eligible to participate in the program. Syracuse University (Department of Electrical Engineering), Purdue University (School of Electrical Engineering), Georgia Institute of Technology (School of Electrical Engineering), and State University of New York at Buffalo (Department of Electrical Engineering) act as prime contractor schools with other schools participating via sub-contracts with the prime schools. The U.S. Air Force Academy (Department of Electrical Engineering), Air Force Institute of Technology (Department of Electrical Engineering), and the Naval Post Graduate School (Department of Electrical Engineering) also participate in the program.

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Further information about the RADC Post-Doctoral Program can be obtained from Mr. Jacob Scherer, RADC/RBC, Griffiss AFB, NY, 13441, telephone Autovon 587-2543, commercial (315) 330-2543.

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ANTENNA PATTERN SYNTHESIS COMPUTER PROGRAM

1. INTRODUCTION

Optimization methods have been successfully applied to the pattern synthesis problem of antenna arrays.[1,2] This application is independent of the functional dependence of the array parameters and therefore treats them on an equal basis. This independence makes the method very general and applicable to a truly large class of problems. Furthermore, the method allows the introduction of a variety of linear and nonlinear constraints in the synthesis, giving the designer the opportunity to simplify the antenna construction. The optimization method in this report is based on one of the well known gradient methods called PARTAN[3,4] implemented in the form of a computer program. The PARTAN method has been selected due to its simplicity in choosing a step size at each iteration and implementing constraints.

2. THE PARTAN OPTIMIZATION METHOD

The radiation patter for $\theta = \theta_o$ of a planar array on the x-y plane can be written as

$$E(\phi) = \sum_{m=1}^{M} (AR_m + jAI_m) e^{jk(x_m \cos\phi + y_m \sin\phi)\sin\theta_o} \qquad (1)$$

where the pair (AR_m, AI_m) specifies the real and imaginary parts of the mth current element and the pair (x_m, y_m) determines the position of the mth element in the x,y plane. M is the number of antenna elements and k is the wave number ($k = 2\pi/\lambda$). In this first treatment the mutual coupling between elements is ignored, and each antenna has an omnidirectional pattern. Later the mutual coupling effect is considered and the current on each antenna is dependent on all other antennas relative positions.

Let $E_s(\phi)$ be the specified or desired radiation pattern. The error over the entire synthesis range can be defined as

$$\varepsilon_1 = \sum_{n=1}^{N} W(\phi_n)\left|E(\phi_n) - E_s(\phi_n)\right|^2 \tag{2}$$

or

$$\varepsilon_2 = \sum_{n=1}^{N} W(\phi_n)\left|\left|E(\phi_n)\right| - \left|E_s(\phi_n)\right|\right|^2 \tag{3}$$

where N is the number of ϕ directions on which the pattern is specified and $W(\phi_n)$ is a weighting function that allows the synthesis precision to be changed over certain ranges of ϕ. Here $W(\phi_n)$ is a non-negative number. When ε_2 is used for the error, only the amplitude of the specified radiation pattern is required. While the amplitude and phase of the specified radiation pattern is required for ε_1. There are some other error definitions, but only ε_1 and ε_2 are used in this report.

Now the problem is to find the minimum of the error function ε by using the PARTAN method. We start with an initial guess for the variables (AR_m^0, AI_m^0, x_m^0, y_m^0), compute the gradient $\nabla\varepsilon^0$ at this point and then compute the new values of the variables (AR_m^0, AI_m^0, x_m^0, y_m^0) as

$$\begin{aligned} AR_m^1 &= AR_m^0 - t\,\frac{\partial\varepsilon^0}{\partial AR_m} & \qquad x_m^1 &= x_m^0 - t\,\frac{\partial\varepsilon^0}{\partial x_m} \\ AI_m^1 &= AI_m^0 - t\,\frac{\partial\varepsilon^0}{\partial AI_m} & \qquad y_m^1 &= y_m^0 - t\,\frac{\partial\varepsilon^0}{\partial y_m} \end{aligned} \tag{4}$$

where the derivatives are evaluated at the initial point. We then continue in a similar fashion until the minimum of ε is found. The problem is to find t, the step size, at each iteration.

Using a Taylor series, we get from Eqs. (1) and (4)

$$E^1(\phi) = \sum_{m=1}^{M} \{(AR_m^0 - t \frac{\partial\varepsilon^0}{\partial AR_m}) + j(AI_m^0 - t \frac{\partial\varepsilon^0}{\partial AI_m}) e^{jk(x_m^0\cos\phi+y_m^0\sin\phi)\sin\theta_0}$$

$$x \{1 - jk \sin \theta_0 (\frac{\partial\varepsilon^0}{\partial x_m} \cos \phi + \frac{\partial\varepsilon^0}{\partial y_m} \sin \phi)t + \ldots\} \quad (5)$$

This is used to calculate the error function ε_1 or ε_2 in Eqs. (2) or (3). After Eq. (5) is substituted into Eq. (2) or (3), and the higher order terms than t^2 are neglected, we get a quadratic equation in t for ε_1 or ε_2. Neglecting higher order terms than t^2 is equivalent to assuming that

$$|k \sin \theta_0 (\frac{\partial\varepsilon^0}{\partial x_m} \cos \phi + \frac{\partial\varepsilon^0}{\partial y_m} \sin \phi)t| << 1 \quad (6)$$

Thus the step size t of each iteration is found in close form from the quadratic equation with respect to t for the minimum ε_1 or ε_2 in the direction $\nabla\varepsilon^0$. This is one of the advantages of approximating Eqs. (2) and (3) with the quadratic equation of t. Even if Eq. (6) is not satisfied in the initial iterations, eventually it will be satisfied and the minimum ε_1 or ε_2 can be obtained.

3. APPLICATION TO SOME SPECIFIC SYNTHESIS PROBLEMS

3.1. All Antennas Are Excited in Linear Antenna Array.

Let us now apply the above ideas to some specific cases.

Let us calculate ε_1^1 by using Eq. (5).

$$\varepsilon_1^1 = \sum_{n=1}^{N} \left| \sum_{m=1}^{M} \left\{ \left(AR_m^0 - t\frac{\partial \varepsilon_1^0}{\partial AR_m}\right) + j\left(AI_m^0 - \frac{\partial \varepsilon_1^0}{\partial AI_m}\right) \right\} \cdot e^{jk\left\{\left(x_m^0 - t\frac{\partial \varepsilon_1^0}{\partial x_m}\right)\cos\phi_n + \left(y_m^0 - t\frac{\partial \varepsilon_1^\theta}{\partial y_m}\right)\sin\phi_n\right\}\sin\theta_0} - E_s(\phi_n) \right|^2 \qquad (7)$$

Neglecting the terms of order higher than t^2, we get

$$\varepsilon_1^1 = \sum_{n=1}^{N} \left| a_n + b_n t + c_n t^2 \right|^2$$

$$= \sum_{n=1}^{N} \{(a_n a_n^*) + (a_n b_n^* + a_n^* b_n)t + (a_n c_n^* + a_n^* c_n + b_n b_n^*)t^2\} \qquad (8)$$

where

$$\left.\begin{aligned}
a_n &= \sum_{m=1}^{M} (AR_m^0 + jAI_m^0) e^{jk(x_m^0\cos\phi_n + y_m^0\sin\phi_m)\sin\theta_0} - E_s(\phi_n) \\
b_n &= -\sum_{m=1}^{M} \left\{\frac{\partial \varepsilon_1^0}{\partial AR_m} + j\frac{\partial \varepsilon_1^0}{\partial AI_m} + jk\sin\theta_0\,(AR_m^0 + jAI_m^0)\left(\cos\phi_n\frac{\partial \varepsilon_1^0}{\partial x_m} + \sin\phi_n\frac{\partial \varepsilon_1^0}{\partial y_m}\right)\right\} \\
&\quad \cdot e^{jk(x_m^0\cos\phi_n + y_m^0\sin\phi_n)\sin\theta_0} \\
c_n &= \sum_{m=1}^{M} \left\{ jk\left(\frac{\partial \varepsilon_1^0}{\partial AR_m} + j\frac{\partial \varepsilon_1^0}{\partial AI_m}\right)\left(\cos\phi_n\frac{\partial \varepsilon_1^0}{\partial x_m} + \sin\phi_n\frac{\partial \varepsilon_1^0}{\partial y_n}\right)\sin\theta_0 \right. \\
&\quad \left. - \frac{k^2\sin\theta_0^2}{2}(AR_m^0 + jAI_m^0)\left[\cos\phi_n\left(\frac{\partial \varepsilon_1^0}{\partial x_m}\right) + \sin\phi_n\left(\frac{\partial \varepsilon_1^0}{\partial y_m}\right)\right]^2 \right\} \\
&\quad \cdot e^{jk(x_m^0\cos\phi_n + y_m^0\sin\phi_n)\sin\theta_0} - E_s(\phi_n).
\end{aligned}\right\} \qquad (9)$$

The derivatives are

$$\left.\begin{aligned}
\frac{\partial \varepsilon_1^0}{\partial AR_m} &= 2\cdot \sum_{n=1}^{N} \mathrm{Re}[(E^1(\phi_n) - E_s(\phi_n))e^{-jk(x_m^0\cos\phi_n + y_m^0\sin\phi_n)\sin\theta_0} \\
\frac{\partial \varepsilon_1^0}{\partial AI_m} &= 2\cdot \sum_{n=1}^{N} I_m[(E^1(\phi_n) - E_s(\phi_n))e^{-jk(x_m^0\cos\phi_n + y_m^0\sin\phi_n)\sin\theta_0}
\end{aligned}\right\} (10)$$

$$\frac{\partial \varepsilon_1^0}{\partial x_m} = 2\cdot \sum_{n=1}^{N} k\cos\phi_n\, I_m[(E^1(\phi_n) - E_s(\phi_n))(AR_m^0 - jAI_m^0)e^{-jk(x_m^0\cos\phi_n + y_n^0\sin\phi_n)\sin\theta_0}]$$

$$\frac{\partial \varepsilon_1^0}{\partial y_m} = 2\cdot \sum_{n=1}^{N} k\sin\phi_n\, I_m[(E^1(\phi_n) - E_s(\phi_n))(AR_m^0 - jAI_m^0)e^{-jk(x_m^0\cos\phi_n + y_m^0\sin\phi_n)\sin\theta_0}]$$

where Re is the real part operator and I_m is the imaginary part operator.

Equation (8) was applied to synthesize the specified pattern shown in Figure 1, which has a triangle shape and has a peak at $\phi = 90°$. The array elements are allowed to move only along the x-axis. Therefore, 24 variables are used for this problem. The weighting function W was set to 1. In the initial guess all amplitudes have been set equal to 1 and the antennas are equally spaced on the x-axis a half wavelength apart.

The second example is the synthesis of the pattern of Figure 2 with 20 dB side lobe level. The array elements are allowed to move only along the x-axis. Therefore, 24 variables are used for this problem also. The weighting function W provides a convenient tool for increasing the accuracy of the synthesis in certain portions of the desired pattern. In this example W is equal to 5 for points in the main beam. In this way emphasis has been placed on obtaining a pattern which has the correct main beam-width. For the side-lobe region, W was set to either 0 or 1, depending on whether

$E_s(\phi_n) - E(\phi_n)$ is positive or negative. In this way, points below the specified side lobe level have no influence in the computation of the error ε_1. In the initial guess all amplitudes have been set equal to 1 and the antennas are equally spaced on the x-axis a half wavelength apart. The final solution is shown in Fig. 2.

3.2 Linear Array with Only One Excited Element and the Others Parasite

The currents on the parasite elements are a function of their relative position and of their distance to the excited antennas. The initial currents on all antennas are obtained by using the method of moments[5], and from this, equivalent point sources are obtained when the constant θ-plane radiation pattern is considered. These point sources correspond to AR_m and jAI_m in Eq. (1). For this problem let ε_2 in Eq. (3) be the error function, since in most cases we are not interested in the phase of the radiation pattern.

$$\varepsilon_2^1 = \sum_{n=1}^{N} W(\phi_n)\left|\,|E^1(\phi_n)| - |E_s(\phi_n)|\,\right|^2 \tag{11}$$

The derivatives to be used are

$$\begin{aligned}
\frac{\partial \varepsilon_2^0}{\partial x_m} &= 2\cdot \sum_{n=1}^{N} \frac{\partial |E^0(\phi_n)|}{\partial x_m} \left(|E^0(\phi_n)| - |E_s(\phi_n)|\right) W(\phi_n) \\
\frac{\partial \varepsilon_2^0}{\partial y_m} &= 2\cdot \sum_{n=1}^{N} \frac{\partial |E^0(\phi_n)|}{\partial y_m} \left(|E^0(\phi_n)| - |E_s(\phi_n)|\right) W(\phi_n)
\end{aligned} \tag{12}$$

The radiation pattern is from Eq. (1)

$$E(\phi_n) = \sum_{m=1}^{M} (AR_m + jAI_m)e^{jk(x_m\cos\phi_n + y_m\sin\phi_n)\sin\theta_0} \tag{13}$$

where $AR_m + jAI_m$ is the function of the positions of all antennas.

If mutual coupling effects of all antennas are considered, the equivalent point sources have to be obtained after each iteration by using the method of moments. This involves a large number of calculations and computer execution time. One way to avoid this problem is to assume that only the mutual coupling between each parasite and the excited antenna is important. Further, we assume that in Eq. (13)

$$AR_m + jAI_m = \frac{I_m^c}{\left(\frac{r_m}{r_m^c}\right)} e^{-jk(r_m - r_m^c)} \tag{14}$$

where I_m^c is the initial equivalent point source and r_m^c is the initial distance between the excited antenna and the mth parasite. For the excited antenna it is assumed that $(r_m/r_m^c) = 1$. For simplicity let us assume that the excited antenna is m = 1. Then we get

$$\begin{aligned} r_m &= \sqrt{(x_m - x_1)^2 + (y_m - y_1)^2} \\ r_m^c &= \sqrt{(x_m^c - x_1^c)^2 + (y_m^c - y_1^c)^2} \end{aligned} \tag{15}$$

where (x_m^c, y_m^c) and (x_1^c, y_1^c) are initial positions of the parasite and the excited antenna respectively.

Now the derivatives $\frac{\partial E^0(\phi_n)}{\partial x_m}$ and $\frac{\partial E^0(\phi_n)}{\partial y_m}$ can be obtained as

$$\frac{\partial E^0(\phi_n)}{\partial x_n} = I_m^c \left(\frac{r_m^c}{r_m}\right) e^{-jk(r_m - r_m^c)} e^{jk(x_m \cos\phi_n + y_m \sin\phi_n)\cdot\sin\theta_0} \left[jk \cos\phi_n - \left(jk + \frac{1}{r_m}\right)\frac{(x_m - x_1)}{r_m}\right]$$

for $m \neq 1$

$$\frac{\partial E^0(\phi_n)}{\partial x_1} = jk\, I_1^c \cos\phi_n\, e^{jk(x_m \cos\phi_n + y_m \sin\phi_n)\cdot\sin\theta_0}$$

$$\frac{\partial E^0(\phi_n)}{\partial y_m} = I_m^c\left(\frac{r_m^c}{r_m}\right)e^{-jk(r_m - r_m^c)}\, e^{jk(x_m\cos\phi_n + y_m\sin\phi_n)\cdot\sin\theta_0}\left[jk\sin\phi_n - \left(jk+\frac{1}{r_m}\right)\frac{(y_m - y_1)}{r_m}\right]$$

$$\left.\begin{aligned} & \text{for } m \neq 1 \\ & \frac{\partial E^0(\phi_n)}{\partial y_1} = jkI_1^c \sin\phi_n e^{jk(x_m\cos\phi_n + y_m\sin\phi_n)\cdot\sin\theta_0} \end{aligned}\right\} \quad (16)$$

Since $|E^0(\phi_n)|^2 = E^0(\phi_n)\cdot E^0(\phi_n)^*$, we get

$$|E^0(\phi_n)|\,\frac{\partial|E^0(\phi_n)|}{\partial x_m} = \mathrm{Re}\left[\frac{\partial E^0(\phi_n)}{\partial x_m}\; E(\phi_n)^*\right]$$

Then

$$\frac{\partial|E^0(\phi_n)|}{\partial x_m} = \frac{\mathrm{Re}\left[\frac{\partial E^0(\phi_n)}{\partial x_m}\; E(\phi_n)^*\right]}{|E^0(\phi_n)|}$$

Similarly

$$\frac{\partial|E^0(\phi_n)|}{\partial y_m} = \frac{\mathrm{Re}\left[\frac{\partial E^0(\phi_n)}{\partial y_m}\; E(\phi_n)^*\right]}{|E^0(\phi_n)|} \quad (17)$$

Substituting Eqs. (16) and (17) into Eqs. (12), we can obtain the value of the derivatives to start the iteration.

From Eqs. (4), (13), (14) and (15), we get

$$E^1(\phi_n) = I_1^c e^{jk[(x_1^0 - t(\partial\varepsilon_2^0/\partial x_1))\cos\Phi_n + (y_1^0 - t(\partial\varepsilon_2^0/\partial y_1))\sin\phi]\sin\theta_0}$$

$$+ \sum_{m=2}^{M} I_m^c r_m^c e^{jkr_m^c}\cdot \frac{e^{-jk\sqrt{(x_m^0 - t(\partial\varepsilon_2^0/\partial x_m) - x_1^0)^2 + (y_m^0 - t(\partial\varepsilon_2^0/\partial y_m) - y_1^0)^2}}}{\sqrt{(x_m^0 - t(\partial\varepsilon_2^0/\partial x_m) - x_1^0)^2 + (y_m^0 - t(\partial\varepsilon_2^0/\partial y_m) - y_1^0)^2}}$$

$$\cdot e^{jk[(x_m^o - t(\partial\varepsilon_2^0/\partial x_m))\cos\phi_n + (y_m^0 - t(\partial\varepsilon_2^0/\partial y_m))\sin\phi_n]\sin\theta_0} \quad (18)$$

By using a Taylor series and neglecting the higher order terms than t^2, we get

$$E^1(\phi_1) = \sum_{m=1}^{M} A_m(1 + B_1 t + B_2 t^2) \tag{19}$$

where

$$A_m = I_m^c\left(\frac{r_m^c}{r_m^o}\right) e^{-jk(r_m^o - r_m^c)} e^{jk(x_m^0 \cos\phi_n + y_m^0 \sin\phi_n)\sin\theta_0}$$

$$B_1 = -jk(g_x \cos\phi_n + g_y \sin\phi_n)\sin\theta_0 + D_1$$

$$D_1 = \begin{cases} 0 & m = 1 \\ \dfrac{(x_m^0 - x_1^0)g_x' + (y_m^0 - y_1^0)g_y}{r_m^0}\left(jk + \dfrac{1}{r_m^0}\right) & m \neq 1 \end{cases}$$

$$B_2 = -\frac{k^2 \sin^2\theta_0}{2}(g_x \cos\phi_n + g_y \sin\phi_n)^2 + D_2$$

$$D_2 = \begin{cases} 0 & m = 1 \\ \dfrac{1}{2}\Bigg[\left\{\dfrac{(x_m^0 - x_1^0)g_x + (y_m^0 - y_1^0)g_y}{(r_m^0)^2}\right\}^2 (3 + jkr_m^0) - \dfrac{g_x^2 + g_y^2}{(r_m^0)^2}(1 + jkr_m^0)\Bigg] & \\ \quad - jk\dfrac{(x_m^0 - x_1^0)g_x + (y_m^0 - y_1^0)g_y}{(r_m^0)^2}\cdot\Bigg\{g_x \cos\phi_n + g_y \sin\phi_n & \\ \quad - \dfrac{(x_m^0 - x_1^0)g_x + (y_m^0 - y_1^0)g_y}{r_m^0}\Bigg\} & m \neq 1 \end{cases}$$

$$g_x = \frac{\partial\varepsilon_2^0}{\partial x_m}$$

$$g_y = \frac{\partial\varepsilon_2^0}{\partial y_m}$$

Eq. (19) can be expressed as

$$E^1(\phi_n) = a + bt + ct^2 \tag{21}$$

where

$$a = \sum_{m=1}^{M} A_m, \qquad b = \sum_{m=1}^{M} A_m B_1, \quad \text{and } C = \sum_{m=1}^{M} A_m B_2$$

Then Eq. (21) is substituted into Eq. (11) and we have

$$\varepsilon_0^1 = \sum_{n=1}^{N} \left(\sqrt{(a + bt + ct^2)(a^* + b^* t + c^* t^2)} - |E_s(\phi_n)| \right)^2 \tag{22}$$

Neglecting the terms of orders higher than t^2, we have

$$\varepsilon_2^1 = \sum_{n=1}^{N} \left(\sqrt{aa^* + (ab^* + a^* b)t + (ac^* + a^* c + bb^*)t^2} - |E_s(\phi_n)| \right)^2$$

$$= \sum_{n=1}^{N} \left[\sqrt{aa^*} - |E_s(\phi_n)| + \frac{ab^* + a^* b}{2\sqrt{aa^*}}\, t + \left(\frac{ac^* + a^* c + bb^*}{2\sqrt{aa^*}} - \frac{(ab^* + a^* b)^2}{4(\sqrt{aa^*})^3} \right) t^2 \right]^2$$

$$= \sum_{n=1}^{N} \left(\sqrt{aa^*} - |E_s(\phi_n)| \right)^2 + \left[\sum_{n=1}^{N} \frac{ab^* + a^* b}{\sqrt{aa^*}} \left(\sqrt{aa^*} - |E_s(\phi_n)| \right) \right] t$$

$$+ \left[\sum_{n=1}^{N} \left\{ \left(\sqrt{aa^*} - |E_s(\phi_n)| \right) \left(\frac{ac^* + a^* c + bb^*}{2\sqrt{aa^*}} \right) + \frac{(ab^* + a^* b)^2}{4(\sqrt{aa^*})^3} |E_s(\phi_n)| \right\} \right] t^2 \tag{23}$$

Equation (23) is a quadratic function of t and the step size t is found easily for the minimum for ε_2^1. This process continues until the change of ε_2^1 is small enough at each iteration.

The assumption of Eq. (14) is now under verification. Preliminary results have shown it to be solid if in computing the current in the parameters the presence of the two adjacent antennas are considered.

4. CONCLUSIONS

The computer programs for the cases discussed in Section 3 have been written and debugged. Once the validity of Eq. (14) or any equivalent formulation is verified, we can proceed with the method.

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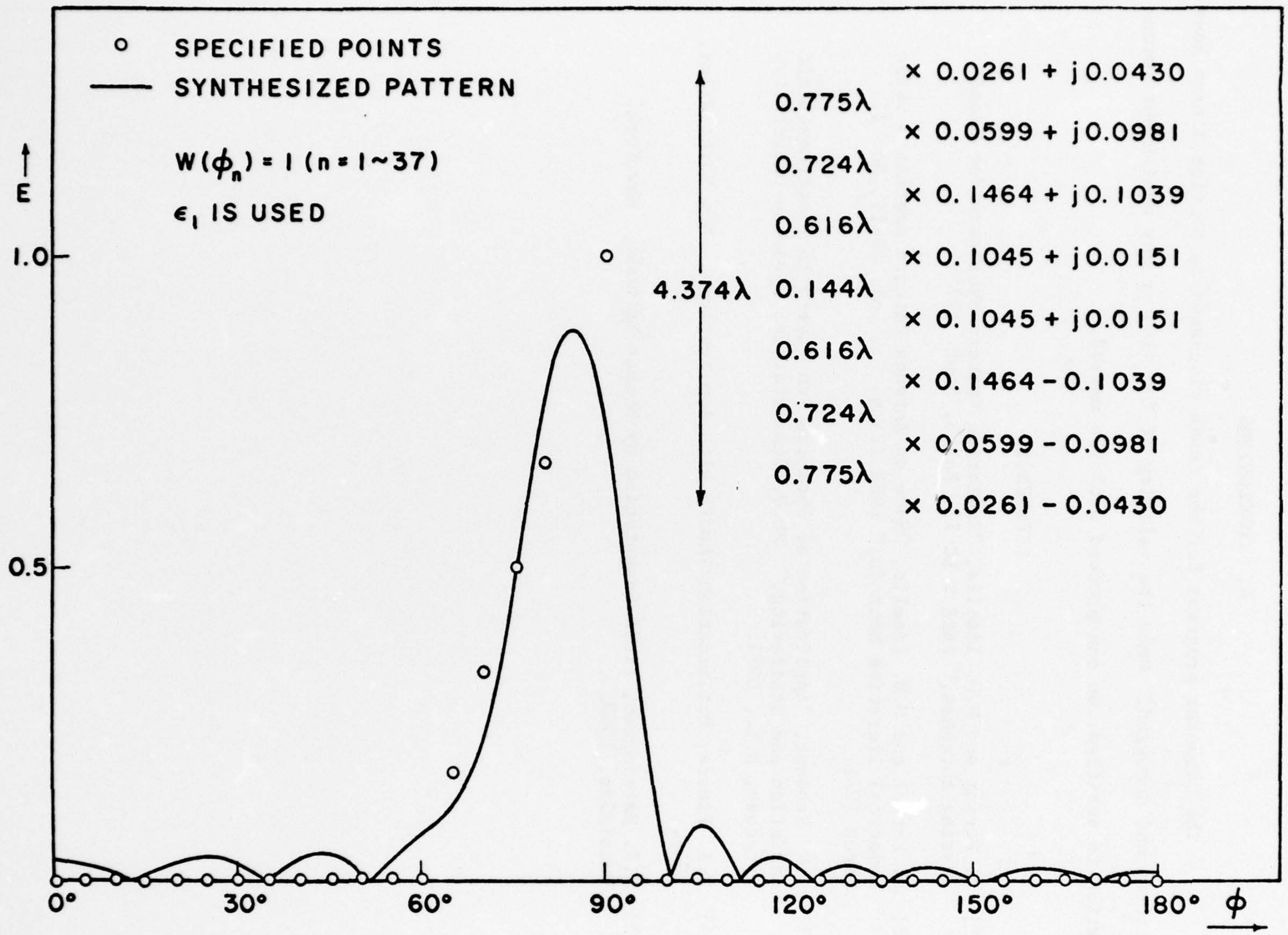
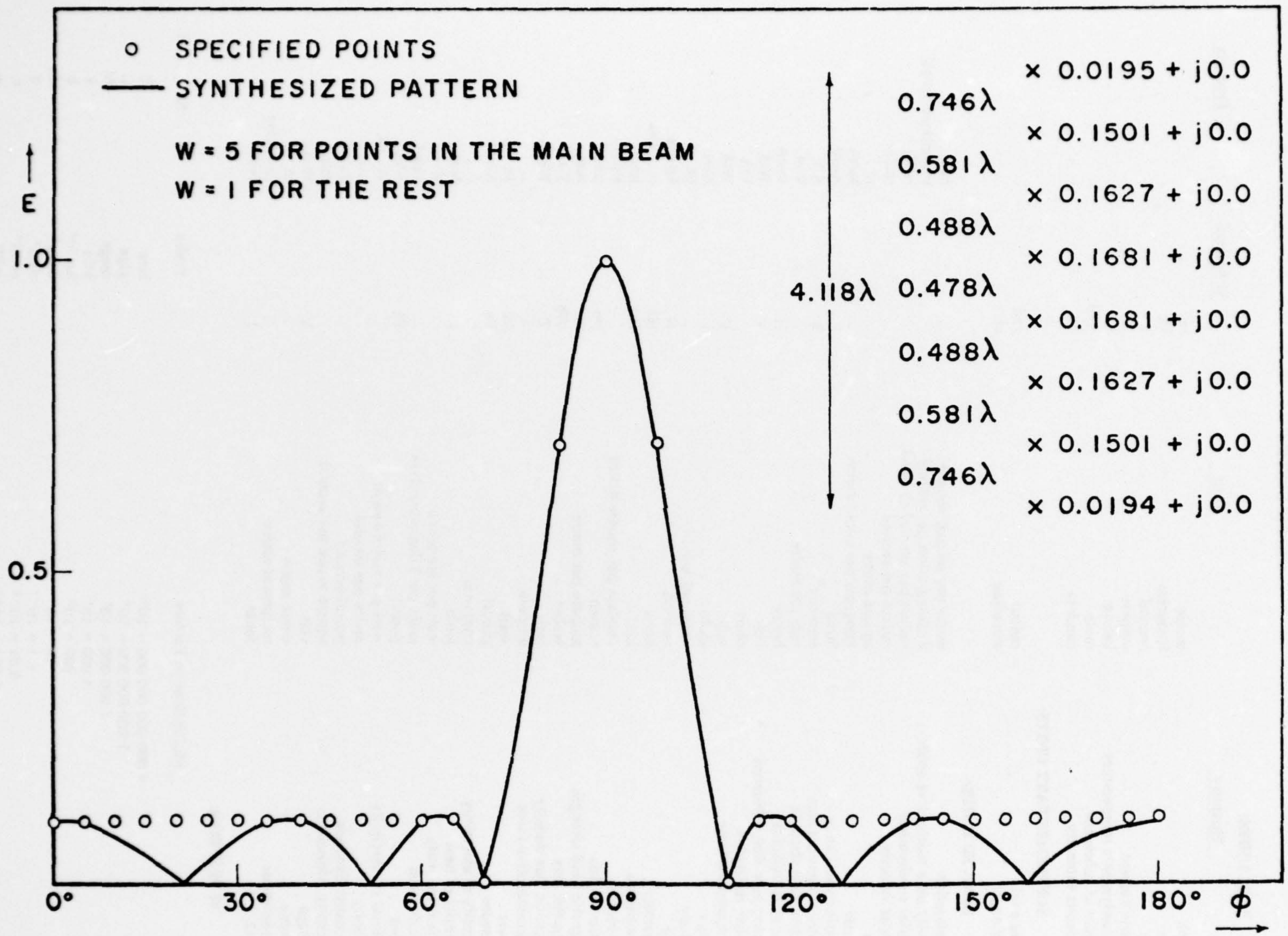

SPECIFIED POINTS
SYNTHESIZED PATTERN
$W(\phi_n) = 1$ $(n = 1 \sim 37)$
ϵ_1 IS USED
E
1.0
0.5
0°
30°
60°
90°
120°
150°
180°
ϕ
4.374λ
0.775λ
0.724λ
0.616λ
0.144λ
0.616λ
0.724λ
0.775λ
× 0.0261 + j0.0430
× 0.0599 + j0.0981
× 0.1464 + j0.1039
× 0.1045 + j0.0151
× 0.1045 + j0.0151
× 0.1464 − 0.1039
× 0.0599 − 0.0981
× 0.0261 − 0.0430

FIGURE



SPECIFIED POINTS
SYNTHESIZED PATTERN
W = 5 FOR POINTS IN THE MAIN BEAM
W = I FOR THE REST
E
1.0
0.5
0°
30°
60°
90°
120°
150°
180°
ϕ
4.118λ
0.746λ
0.581λ
0.488λ
0.478λ
0.488λ
0.581λ
0.746λ
× 0.0195 + j0.0
× 0.1501 + j0.0
× 0.1627 + j0.0
× 0.1681 + j0.0
× 0.1681 + j0.0
× 0.1627 + j0.0
× 0.1501 + j0.0
× 0.0194 + j0.0

FIGURE 2

METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

Quantity	Unit	SI Symbol	Formula
plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Quantity	Unit	SI Symbol	Formula
Acceleration	metre per second squared	...	m/s
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s
angular velocity	radian per second	...	rad/s
area	square metre	...	m
density	kilogram per cubic metre	...	kg/m
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	kg·m/s
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m
luminance	candela per square metre	...	cd/m
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m
thermal conductivity	watt per metre-kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal-second	...	Pa·s
viscosity, kinematic	square metre per second	...	m/s
voltage	volt	V	W/A
volume	cubic metre	...	m
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

* To be avoided where possible.

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